

# The effect of lining segmentation on the reliability of hybrid ceramic/ steel gun barrels

M. Grujicic<sup>a,\*</sup>, J.R. DeLong<sup>a</sup>, W.S. DeRosset<sup>b</sup>

<sup>a</sup>*Department of Mechanical Engineering, Clemson University, Clemson, SC 29634, USA*

<sup>b</sup>*Army Research Laboratory—Processing and Properties Branch, Aberdeen, Proving Ground, MD 21005-5069, USA*

Received 21 June 2002; received in revised form 23 August 2002; accepted 4 September 2002

---

## Abstract

The effect of  $\alpha$ -SiC-lining segmentation on the failure probability of a gun-barrel lining during single-shot and burst firing events has been studied by combining finite-element method based thermo-mechanical calculations with the Weibull statistical structural reliability analysis. The results obtained reveal that, due to a lining/jacket slippage near the barrel ends and due to  $\alpha$ -SiC-lining/CrMoV-steel-jacket thermal-expansion mismatch, tensile axial stresses develop in both single-piece and segmented ceramic liners near the barrel ends. These stresses can become sufficiently high, particularly during the burst firing case, so that they can induce formation of the circumferential cracks and, in turn, lining failure. The lining failure probability has been computed for a single-round and a ten-round burst firing mode. Lining segmentation is found to be beneficial, particularly in the ten-round case where it can reduce the lining failure probability by as much as 18%.

© 2002 Elsevier Science Ltd. All rights reserved.

**Keywords:** Impact and ballistic; Brittle fracture

---

## 1. Introduction

It is generally recognized, e.g. [1] that CrMoV-based steels which are traditionally used for large-caliber gun barrels operate near their limits of thermal cracking and melting erosion resistances during long-burst firing. This is particularly true when advanced high-energy propellants are used. One of the approaches to enhancing the performance of such guns is the use of hybrid gun barrels consisting of a ceramic liner and a steel jacket. Due to their high melting temperature (controls melting-erosion resistance), high hot-hardness (controls wear and erosion resistances), and chemical inertness (controls corrosion-erosion resistance), ceramics appear as quite attractive materials in barrel liner applications. However, ceramics suffer from a lack of fracture toughness and tensile strength, which currently limits their wide use in advanced gun barrels [2,3].

Experimental investigations of the ceramic-lined gun barrels carried out over the last two decades have established that: (a)  $\alpha$ -SiC,  $\text{Si}_3\text{N}_4$  and  $\text{SiAlON}$  (a  $\text{Si}_3\text{N}_4 + \text{Al}_2\text{O}_3$  solid solution) gun-barrel ceramic liners show the best performance and are capable of surviving at least 1000 rounds in the single-shot mode and over 100 rounds in the burst-firing mode of conventional ammunition with standard M2 propellant in a 0.50 caliber machine gun; (b) the primary failure mode in these barrels is the formation of circumferential cracks near the barrel ends; and (c) only  $\alpha$ -SiC liners have so far been tested in single-shot and burst firing modes using specially designed ammunition and the JA-2 high-energy propellant (flame temperature  $\sim 3450$  K) in a 25-mm-bore gun barrel. This propellant gives rise to a  $\sim 17\%$  increase in the projectile velocity at the muzzle-end of the barrel relative to that attained using the standard M2 propellant. These  $\alpha$ -SiC liners also suffer from formation of multiple circumferential cracks near the breach and muzzle ends with the first crack being observed after the first 100-round burst. An important observation was also made that, while each end of the liner was converted to a stack of washers, the cracks

---

\*Corresponding author. 241 Engineering Innovation Building, Clemson, SC 29634-0921, USA. Tel.: +1-864-656-5639; fax: +864-656-4435.

E-mail address: [mica.grujicic@ces.clemson.edu](mailto:mica.grujicic@ces.clemson.edu) (M. Grujicic).

Report Documentation Page			Form Approved OMB No. 0704-0188	
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.				
1. REPORT DATE <b>2003</b>	2. REPORT TYPE		3. DATES COVERED <b>00-00-2003 to 00-00-2003</b>	
4. TITLE AND SUBTITLE <b>The effect of lining segmentation on the reliability of hybrid ceramic/steel gun barrels</b>			5a. CONTRACT NUMBER	
			5b. GRANT NUMBER	
			5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)			5d. PROJECT NUMBER	
			5e. TASK NUMBER	
			5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) <b>Clemson University, Department of Mechanical Engineering, Clemson, SC, 29634</b>			8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)			10. SPONSOR/MONITOR'S ACRONYM(S)	
			11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT <b>Approved for public release; distribution unlimited</b>				
13. SUPPLEMENTARY NOTES				
14. ABSTRACT <b>The effect of a-SiC-lining segmentation on the failure probability of a gun-barrel lining during single-shot and burst firing events has been studied by combining finite-element method based thermo-mechanical calculations with the Weibull statistical structural reliability analysis. The results obtained reveal that, due to a liningjacket slippage near the barrel ends and due to a- SiC-liningyCrMoV-steel-jacket thermal-expansion mismatch, tensile axial stresses develop in both single-piece and segmented ceramic liners near the barrel ends. These stresses can become sufficiently high, particularly during the burst firing case, so that they can induce formation of the circumferential cracks and, in turn, lining failure. The lining failure probability has been computed for a single-round and a ten-round burst firing mode. Lining segmentation is found to be beneficial, particularly in the ten-round case where it can reduce the lining failure probability by as much as 18%.</b>				
15. SUBJECT TERMS				
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT <b>Same as Report (SAR)</b>	18. NUMBER OF PAGES <b>10</b>
a. REPORT <b>unclassified</b>	b. ABSTRACT <b>unclassified</b>	c. THIS PAGE <b>unclassified</b>		

were ‘tight’ (no evidence of gas leakage to the steel jacket) and they did not apparently degrade the gun performance. In fact, burst-firing tests were terminated not due to degradation of the barrel lining but due to excessive erosion in the non-lined CrMoV-steel barrel extender [4].

In our recent work [5], a combined thermal/mechanical finite element analysis of hybrid  $\alpha$ -SiC ceramic lining/CrMoV-steel jacket gun barrels was carried out in order to understand the origin of lining failure during single-shot and burst ballistic events. It is found that, as the steel jacket heats up and expands during a firing cycle, it pulls on the ceramic lining causing the ends of the lining to be subjected to axial stress levels as high as 280 MPa and 350 MPa for the single-shot and burst firing events, respectively. Under such high levels of tensile stresses, the application of the Weibull structural reliability analysis yielded the corresponding failure probabilities of 0.002 and 0.0121. These findings are found to be consistent with the experimental results which showed that formation of axial cracks occurs after  $\sim 1000$  single-shot rounds and after  $\sim 100$  burst rounds [6].

In the present paper, a combined thermal/mechanical finite element analysis is integrated with the Weibull structural reliability analysis in order to assess the effect of lining segmentation on the failure probability of the lining. It has been suggested [6] that, if the ceramic lining is composed of several cylindrical segments stacked next to each other, the level of tensile axial stresses which can be built inside each segment and, hence, the failure probability should be reduced relative to that in the corresponding single-piece lining.

The organization of this paper is as follows: a procedure used to calculate boundary conditions at the interior surface of the gun barrel needed in the finite-element analysis of gun barrel heating during single-shot and burst firing is presented in Section 2.1. A brief overview of the structural reliability analysis and its application to gun barrels during single-shot and burst firing is given in Section 2.2. Thermal and mechanical finite element analyses of the behavior of gun barrels containing single-piece and segmented linings during single-shot and burst firing events are discussed in Section 2.3. The main findings obtained in the present work are presented and discussed in Section 3. The key conclusions resulting from the present work are given in Section 4.

## 2. Computational procedures

### 2.1. Determination of thermal boundary conditions at the inner surface of the gun barrel

During a firing cycle, the gun barrel heats up due to forced convection of hot combustion gas, sliding friction

of the projectile and obturator galling. In addition, radiation can be significant in the breech region. Through the use of plastic obturators, the contributions of friction and galling to gun barrel heating can be reduced to a level at which they can be considered as insignificant. Moreover, since the contribution of radiation is very small along the major portion of the gun-barrel length, it is generally not included in the analysis of barrel heating. In other words, such an analysis generally includes forced convection heat transfer at the interior barrel surface, heat conduction through the barrel wall and natural convection and radiation heat transfer at the outer barrel surface.

The computation of forced-convection boundary conditions (the film temperature and the heat transfer coefficient) at the interior barrel wall is carried out in the present work using the following two computer codes: (a) the XKTC one-dimensional internal ballistic code [7] which provides spatial and temporal evolution of the film temperature, pressure and gas velocity during a single-shot firing event and; (b) the XBR2D code [8–11] which enables the calculation of the pressure, gas velocity, and compressibility dependent convective heat transfer coefficient. A detailed description of such calculations can be found in our recent work [5] and therefore will not be repeated here. In addition, all input parameters used in the calculations of thermal boundary conditions at the inner surface of the gun barrel can be found in Table I of Grujicic et al. [5].

### 2.2. Reliability analysis of structural components

The design of ceramic components differs from that for components made of ductile metals due to the inability of ceramics to redistribute high local stresses induced by the inherent flaws. The random nature of the size and orientation of flaws and the resulting absence of a unique strength in ceramics demand a probabilistic approach in the design involving these materials. The strength response of ceramic materials is generally well represented using the weakest link concept within which the ceramic component under consideration is modeled as a series of links (as in a chain). The weakest link concept was first used by Weibull [12] and subsequently by Batdorf and Crose [13] to derive stress volume- and stress area-integrals to predict the failure response of ceramic materials. These integrals take into account the fact that failure is not necessarily governed by the most highly stressed location in a component (the presence of potent stress-enhancing flaws plays an equally important role) but rather by its entire stress field. Another important (and experimentally established) phenomenon captured by the weakest link theory is that the strength of a component decreases with an increase in its volume and/or surface area.

Within the Weibull theory, the effect of size but not the orientation of the flaws is considered. The effect of multi-axial stress states is handled by either averaging the normal stresses [12] or by using the principle of independent action within which each tensile stress contributes to the failure probability as if no other stresses were present [14,15]. The theory of Batdorf and Crose [13] combines the weakest link approach with the theory of linear elastic fracture mechanics. Consequently, effects of both the flaw size and the flaw orientation relative to the applied stress are included. The model of Batdorf and Crose was subsequently extended by Batdorf and Heinisch [16] to include mixed-mode fracture. The reliability of hybrid  $\alpha$ -SiC-lining/CrMoV steel-jacket gun barrels is analyzed in the present work using the Weibull structural-component reliability theory.

Phenomenological observations suggest that the failure of monolithic-ceramics is consistent with the weakest-link principle. The weakest link principle is readily understood by analyzing a chain which, as is being pulled, will fail catastrophically when its weakest link breaks. The reliability of such a chain is given as the product of the survival probabilities of its individual links. For failure controlled by surface defects as in the present case, Weibull [12] derived the following expression for the probability of failure,  $P_{fs}$ , of a ceramic component loaded in uniaxial tension:

$$P_{fs} = 1 - \exp \left[ - \int_S N_s(\sigma) dS \right] = 1 - \exp[-B_s] \quad (1)$$

where  $S$  is the component surface, subscript  $S$  denotes surface dependant terms,  $N_s(\sigma)$  is commonly referred to as the crack density function and  $B_s$  is the so-called risk of rupture. The following two-parameter power-law function for  $N_s(\sigma)$  is generally used:

$$N_s(\sigma) = \left( \frac{\sigma_n}{\sigma_{os}} \right)^{m_s} \quad (2)$$

where  $\sigma_{os}$  is known as the scale parameter and corresponds to the stress level up to which 63.2% of specimens with unit surface area would fracture and it has dimensions  $\text{stress} \times (\text{area})^{1/m_s}$  where  $m_s$  is the shape parameter (also referred to as the Weibull modulus or Weibull slope) and is a measure of the degree of strength dispersion. The Weibull statistical parameters,  $\sigma_{os}$  and  $m_s$ , for a given ceramic material are generally dependant on the testing temperature, specimen geometry, loading type and the material's processing history and micro-structure. These parameters for the  $\alpha$ -SiC gun-barrel lining material have been evaluated in our recent work [5] using the fracture data for O-ring specimens tested in diametral compression [6].

To predict material response under multiaxial stress conditions, Weibull [12] proposed the normal stress averaging method as:

$$P_{fs} = 1 - \exp \left[ - \int_S \left( \frac{\bar{\sigma}_n}{\sigma_{ops}} \right)^{m_s} dS \right] \quad (3)$$

where

$$\bar{\sigma}_n^{m_s} = \frac{\int_l \sigma_n^{m_s}}{\int_l dl} \quad (4)$$

The line integration in Eq. (4) is performed in a principle stress area over the arc  $l$  of a unit circle over which the projected normal stress  $\sigma_n$  is tensile. The multiaxial Weibull scale parameter  $\sigma_{ops}$  is found to be a simple function of its uniaxial counterpart  $\sigma_{os}$  [12].

Barnett and Freudenthal [14,15] subsequently proposed the principle of independent action to predict material behavior under multiaxial stress conditions as:

$$P_{fs} = 1 - \exp \left[ \int_A ((\sigma_1^{m_s} + \sigma_2^{m_s}) / \sigma_{os}^{m_s}) dA \right] \quad (5)$$

where the principle stresses  $\sigma_1$ , and  $\sigma_2$  are used in Eq. (5) provided they are tensile. Otherwise, each compressive principal stress is set to zero in this equation.

### 2.3. Finite element analysis

#### 2.3.1. Description of the problem

A schematic of a gun-barrel assembly used for testing  $\alpha$ -SiC barrel liners under single-shot and burst-firing modes is shown in Fig. 1. The barrel is 355.6 mm long, has a 25.0-mm bore and the  $\alpha$ -SiC lining is 3.175 mm thick. In the present work, the  $\alpha$ -SiC lining is considered to be either a single-piece insert or to be composed of five individual cylindrical segments each 71.12 mm long. The wall thickness of the steel jacket is approximately 25.4 mm. As shown in Fig. 1, the barrel assembly also includes a (non-lined) steel barrel extender and a steel shank. Minor components in the barrel assembly such as set screws, compliant washers and a seal are not shown to keep the figure simple. Also, a 0.15-mm-thick lining/jacket compliant interlayer made of copper (often employed to reduce point-type contact stresses at the liner/jacket interface) is not shown. Since point-type contact stresses (controlled by roughness of the contacting surfaces) are not modeled within the present work, the compliant copper layer is not considered.

In order to attain a triaxial compressive stress state in the ceramic lining, the steel jacket is typically placed over it using a shrink-fit process. Within this process, the jacket is heated to a sufficiently high temperature in order to expand its bore and slid over the tubular ceramic lining. Since the (ambient temperature) ceramic-lining outer diameter is larger than the (ambient temperature) steel-jacket inner diameter, the lining prevents a com-

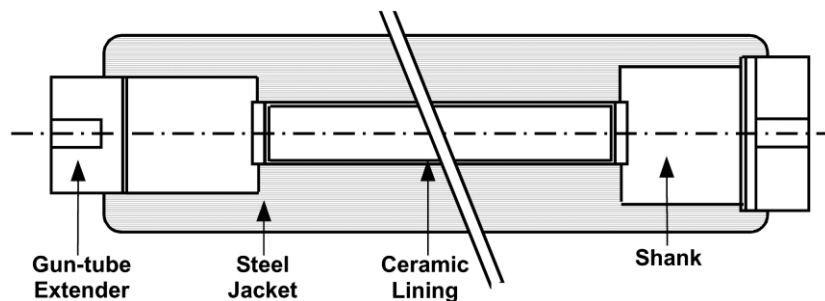


Fig. 1. A schematic of the hybrid ceramic/steel gun barrel.

plete contraction of the jacket during cooling and the resulting hybrid ceramic/steel tube develops residual stresses. In particular, since the steel jacket is prevented from fully contracting by the ceramic lining, it acquires a tensile stress state. Conversely, (triaxial) compressive residual stresses develop in the ceramic lining. Since the ability of ceramics to withstand compressive stresses is at least an order of magnitude higher than their tensile strength, it is generally desirable to maximize the level of compressive residual stresses in the lining. The maximum achievable level of residual stresses in ceramic linings is typically limited by at least two factors: (a) tensile contact stresses at the ceramic/steel interface, if sufficiently high, can give rise to crack formation in the ceramic lining and; (b) the maximum temperature to which the steel jacket is heated (which controls the level of residual stresses) is limited by the requirement that no significant changes in the steel microstructure take place during the shrink fit process.

### 2.3.2. Formulation of the problem

Development of the stresses during single-shot and burst-firing events is modeled in two steps: (a) a transient heat transfer analysis is first carried out in order to determine the temperature evolution during the firing events; and (b) an elastic–plastic mechanical stress analysis is next conducted in order to compute the corresponding evolution of stresses in the hybrid ceramic/steel gun barrel. Decoupling of the thermal analysis and the mechanical analysis is justified since, due to a low extent of plastic deformation in the barrel and limited slippage at the ceramic/steel interface, the contribution of the plastic strain energy and friction dissipated as heat to the energy conservation equation (solved during the thermal analysis) is expected to be minimal while the effect of temperature on the mechanical materials properties can be incorporated directly in the mechanical analysis. All calculations are carried out using the commercial finite element package ABAQUS/Standard [17]. Values of the materials properties used can be found in Table II of Grujicic et al. [5].

A schematic of the model used in the thermal analysis is shown in Fig. 2a. In the initial condition, the temper-

atures of the ceramic lining and the steel jacket are set to room temperature (298 K). A heat transfer by conduction is considered to take place throughout the solid material while heat exchange between the solid and the surrounding is taken to be controlled by convection and radiation. The boundary conditions are set as follows. At the outer surface of the barrel, as well as along the barrel edges, the film temperature, the natural-convection heat transfer coefficient and emissivity are set to fixed values. Along the inner surface of the barrel, the film temperature and the forced-convection heat transfer coefficient are taken to evolve temporally as predicted by calculations based on the combined use of the XKTC and XBR2D codes (Section 2.1). Along the same surface, emissivity is set to a fixed value.

A schematic of the model used in the mechanical finite element analysis is shown in Fig. 2b. In the initial condition, the ceramic lining and the steel jacket are both taken to contain residual stresses introduced by the shrink-fit process and to be both at room temperature. As time progresses during a firing event, differences in temperatures and thermal expansion coefficients of the ceramic lining and the steel jacket give rise to the formation of thermal stresses.  $\alpha$ -SiC is modeled as a linear-elastic isotropic material while the CrMoV steel is modeled as a linear elastic/perfectly plastic isotropic material. Plasticity in the steel jacket has been modeled using the  $J_2$  deformation theory. Temperature dependent mechanical properties of  $\alpha$ -SiC and the CrMoV steel used can be found in Table II of Grujicic et al. [5].

The contact interactions between the ceramic lining and the steel jacket as well as between the adjacent segments of the lining are modeled as follows. No pressure is allowed to be transmitted between the contacting bodies until the corresponding surfaces contact each other. Sliding, i.e. relative motion of the two surfaces of a finite magnitude, is allowed to take place and a fixed value ( $=0.3$ ) of the friction coefficient is assumed.

The finite element mesh used in both thermal and mechanical analyses is shown in Fig. 2c. It should be noted that in order to improve clarity, only one-fifth of the computational domain in the axial direction is shown

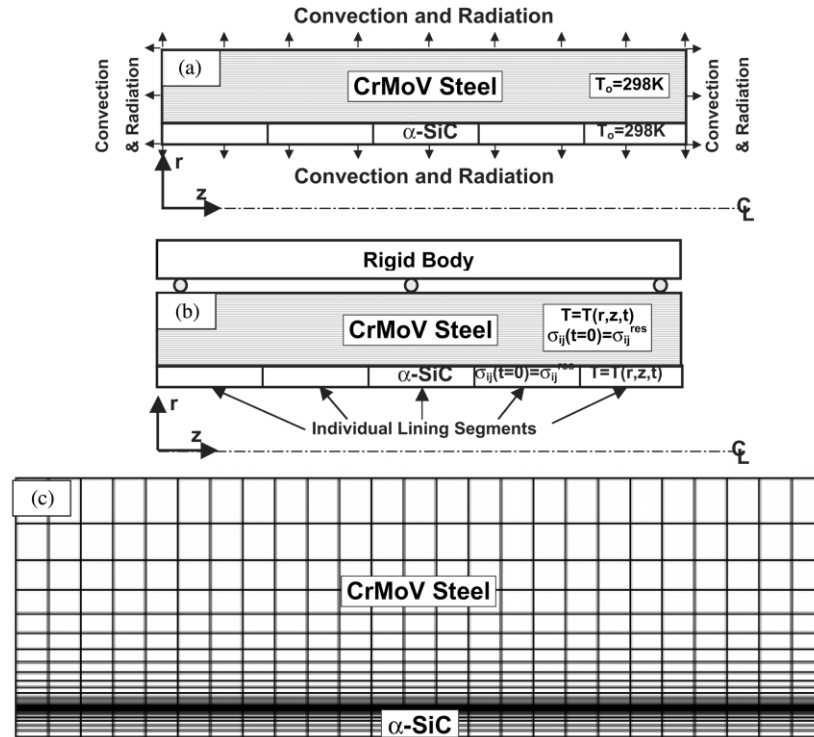


Fig. 2. Models for: (a) thermal and (b) mechanical finite element analyses and (c) the finite element mesh used in the present work.

in Fig. 2c. The computational domain is partitioned into 2400 eight-node quadrilateral axisymmetric elements (DCAX8 ABAQUS elements for the thermal analysis and CAX8 ABAQUS elements for the mechanical analysis). Eight hundred of these elements are located in the ceramic lining (equally distributed between five lining segments) and the remaining 1600 in the steel jacket. In addition, in order to obtain the information about in-plane stresses at the lining/jacket interface (used in the surface-flaw controlled structural reliability analysis of the ceramic lining), a one layer thick row of three-node membrane (MAX2 ABAQUS) elements is placed along this interface. These elements are assigned the mechanical properties of  $\alpha$ -SiC and their thickness is chosen to be very small (0.00001 mm) in order to minimize their effect on the stress results. Moreover, since high-gradients of the stresses are localized to a region adjacent to the lining/jacket interface, mesh refinement is employed in this region.

### 3. Results and discussion

#### 3.1. Effect of lining segmentation on shrink-fit induced residual stresses

In this section, the thermal and mechanical finite element analyses described in detail in Grujicic et al. [5] are used to study the effect of lining segmentation on the distribution and the magnitude of residual stresses

produced by a shrink-fit process in which the steel jacket is heated to a temperature of 973 K and slid over the ceramic lining. For brevity, details of these finite element analyses are not presented in the present paper. Contour plots of the axial ( $\sigma_{zz}$ ) residual stress in the hybrid  $\alpha$ -SiC/CrMoV steel gun barrel induced by such a shrink-fit process are shown in Fig. 3a,b for single-piece and segmented linings, respectively. Only the results for the axial stress are presented here since this stress is found to control formation of the circumferential cracks [5]. It should be noted that only the results pertaining to the left-most quarter of the barrel length (the quarter adjacent to the muzzle end of the barrel) are displayed in Fig. 3a,b. Due to symmetry of the initial and boundary conditions used in both the thermal and the mechanical analyses of the shrink-fit process, the results are symmetric about the plane bisecting the barrel in the axial direction. For the single piece lining, the residual stresses (the results not shown for brevity) are effectively independent of the axial coordinate over approximately one-third of the barrel length in the mid-section of the barrel. In the case of a segmented lining, however, the stresses are slightly affected by the presence of segment/segment contact surfaces. It should be noted that in order to denote the location of the segment/segment interface, a line traversing the entire barrel wall thickness has been drawn at the appropriate axial position in both single-piece and segmented liners. Furthermore, to improve clarity, the aspect ratio in Fig. 3a,b

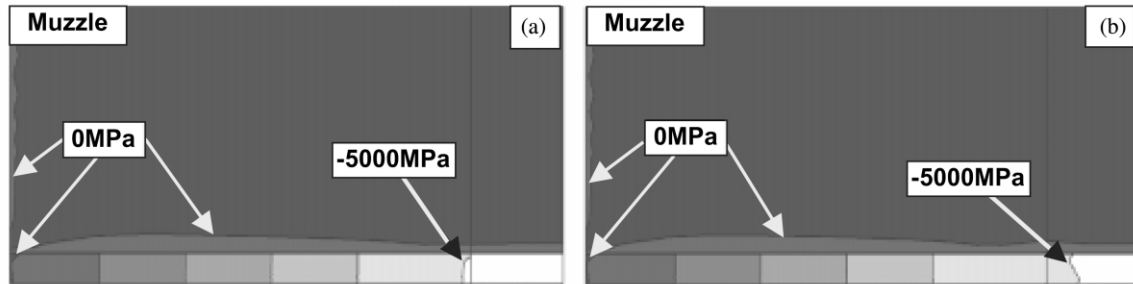


Fig. 3. Distributions of the residual axial stress  $\sigma_{zz}$  induced by a shrink-fit process in gun-barrels with: (a) single-piece and (b) segmented ceramic lining. Adjacent contour lines are 1000 MPa apart.

(and in the subsequent figures containing contour plots) is increased in the  $r$  direction by 50%.

A simple examination of the results shown in Fig. 3a,b reveals that almost the entire  $\alpha$ -SiC lining is subjected to compressive axial stresses. Only a small region at the end of the barrel (the left edge in Fig. 3a,b) is under a tensile axial stress whose maximum value is 254.8 MPa and 255.2 MPa, for the single piece and segmented linings, respectively. These levels of the tensile stress are relatively small in comparison to the magnitudes of the compressive circumferential and radial stress in the same region (approx. 460 MPa and 75 MPa) for both types of lining. Thus, lining sections near the barrel ends, like the rest of the lining, are initially under hydrostatic compression, but of a lower magnitude. Furthermore, the results shown in Fig. 3a,b suggest that lining segmentation does not significantly affect the distribution and the magnitude of residual stresses near the barrel ends. The residual stress results, such as the

ones displayed in Fig. 3a,b, obtained by the finite element modeling of the shrink-fit process are introduced, as initial stresses, in the present finite element analysis of the development of thermal stresses in the gun barrel during single-shot and burst-firing events using a SIGINI Abaqus User Subroutine [17].

### 3.2. Effect of lining segmentation on probability for lining failure

#### 3.2.1. Single-shot firing mode

The variation of the film temperature and the forced-convection heat-transfer coefficient (obtained respectively using the XKTC internal ballistic code [7], and the XBR-2D heat transfer code [8–10]) along the barrel length at several different times following a single-shot ballistic event for a single-piece lining are shown in Fig. 4a,b, respectively. Lining segmentation is found not to affect these results to any significant extent. The results

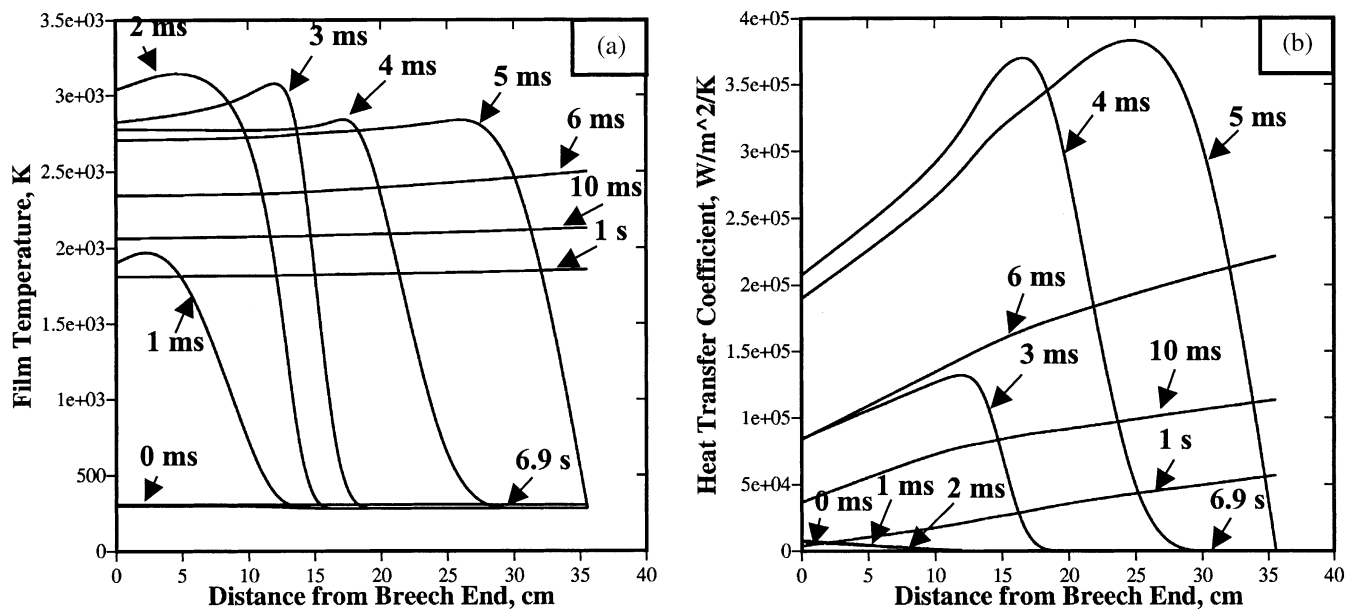


Fig. 4. Variations of: (a) the film temperature and (b) the forced-convection heat transfer coefficient along the inner surface of the barrel as a function of time during a single-shot firing event for a single-piece lining.

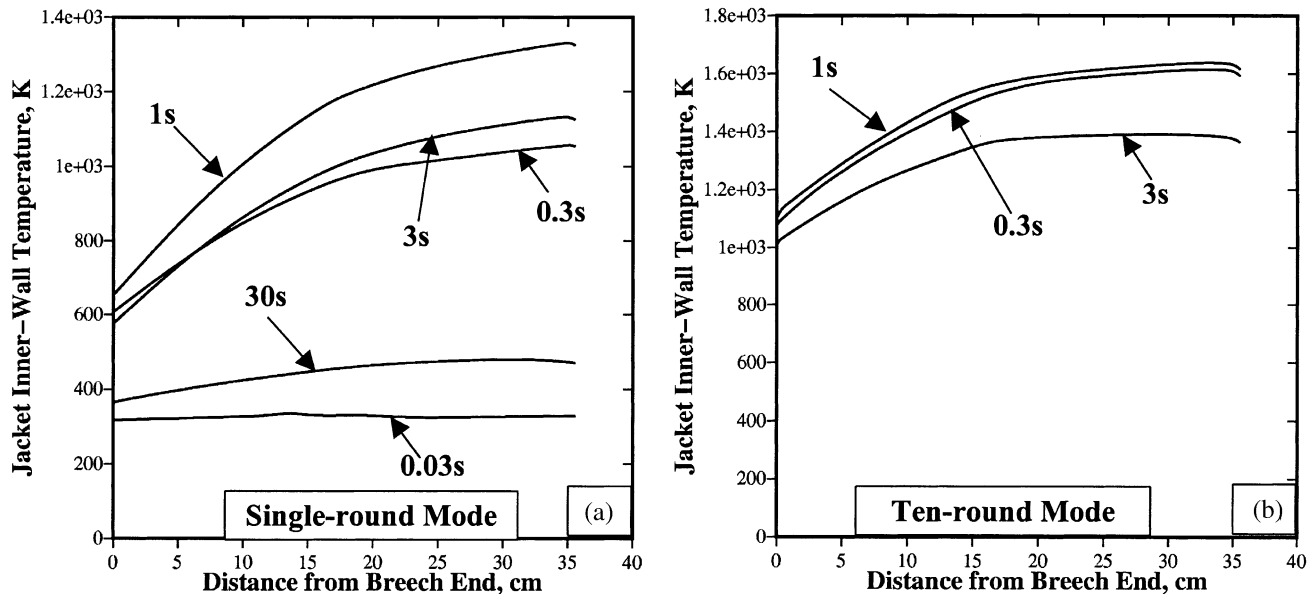


Fig. 5. Variation of the temperature at the inner surface of the steel jacket as a function of time following the firing of the last shot for: (a) a single-round and (b) a 10-round ballistic event.

shown in Fig. 4a indicate that it takes approximately 5 ms for the heat wave resulting from propellant combustion and projectile motion to traverse the barrel length. At times longer than approximately 6 ms following the ignition, the film temperature distribution along the barrel length is quite uniform and decreases monotonically with time.

The forced-convection heat-transfer coefficient results displayed in Fig. 4b indicate that the values of this coefficient vary over a large range (between  $135 \text{ W/m}^2 \text{ per K}$  corresponding to its value for natural convection and  $\sim 380\,000 \text{ W/m}^2 \text{ per K}$  over a middle section of the barrel at a time of 5 ms following the ignition). It should be also noted that only a minor increase in the heat transfer coefficient relative to its natural-convection value occurs during the first two microseconds following the ignition. Lining segmentation is found not to affect these results to any significant extent.

The film temperature and the heat-transfer coefficient results displayed in Fig. 4a,b are used as time-dependant boundary conditions along the inner surface of the barrel for the thermal finite element analysis of a single-shot ballistic event. This is accomplished by incorporating the results shown in Fig. 4a,b into a FILM Abaqus User Subroutine [17].

Since thermal expansion of the steel jacket, brought about by the heat generated during a ballistic event, and the subsequent development of the axial tensile stresses in the ceramic lining near the barrel edges are found to be the main cause for lining failure [5], the distribution of the temperature and its time evolution in the steel jacket at the lining/jacket contact surface are shown in Fig. 5a. The results shown in Fig. 5a indicate that the

maximum temperature experienced by the portion of the steel jacket near the lining/jacket contact surface during a single shot event is approximately 1330 K and that this occurs near the muzzle end approximately 1 s after ignition. In addition the results displayed in Fig. 5a show that, as time following the ignition increases, the heat generated during combustion of the propellant and due to friction at the projectile/barrel contact surfaces propagates from the inner surface of the barrel into the barrel interior and along the barrel length. However, the rate at which the heat wave propagates into the barrel interior is considerably lower than that for the film-temperature wave, Fig. 4a. This finding can be readily explained. Using a volume-averaged thermal conductivity of the ceramic/steel hybrid barrel and the convective heat transfer coefficient results shown in Fig. 4b, the Biot number, (which is defined as a ratio of the conduction and convection heat-transfer resistances), has been found to be as high as 170 for the largest values of the forced-convection heat transfer coefficient. Such a large value of the Biot number implies that, at the times shortly after ignition, when the forced-convection heat transfer coefficient is very large, the heat transfer is conduction controlled and, hence, the rate at which the barrel interior heats up is considerably slower than the rate at which the film temperature evolves along the inner surface of the barrel.

The distribution of the axial stress,  $\sigma_{zz}$ , throughout the wall of the hybrid ceramic/steel gun barrel near the barrel ends at a time of 1 s following a single-shot ballistic event for the single piece and the segmented linings are shown in Fig. 6a–d, respectively. As previously shown in Fig. 5a, at this time instant, thermal



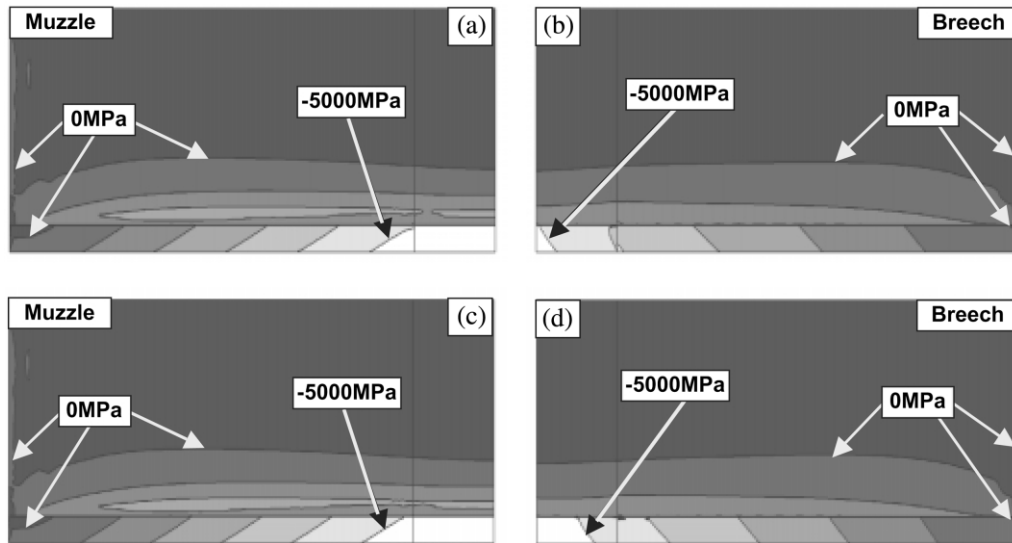


Fig. 6. Distributions of the axial stress near the muzzle and breech ends in barrels with a single-piece (a,b) and a segmented (c,d) lining at a time of 1 s following a single-round firing. Adjacent contour lines are 1000 MPa apart.

expansion of the portion of the steel jacket in contact with the ceramic lining is the largest. The axial stress is of particular interest since, as disclosed earlier, failure of the ceramic lining is generally caused by formation of the  $\sigma_{zz}$ -induced circumferential cracks. The results shown in Fig. 6a–d indicate that regions of the ceramic lining at the lining/jacket interface adjacent to both the muzzle and the breech ends of the barrel are subjected to tensile  $\sigma_{zz}$  stresses. Hence, there is a finite probability for the formation of circumferential cracks in these regions of the ceramic lining. Furthermore, circumferential cracks are most likely to nucleate at the lining/jacket interface where the tensile  $\sigma_{zz}$  stresses are found to have the highest values. This finding is in excellent agreement with the experimental observations, e.g. [2]. The largest values of  $\sigma_{zz}$  in the lining at the breech and the muzzle barrel ends are found to be  $\sim 170.0$  MPa and 384.6 MPa in the single-piece lining and 170.1 MPa and 376.1 MPa in the segmented lining, respectively. This finding suggests that the likelihood for formation of circumferential cracks is significantly higher at the muzzle end, which is also consistent with the experimental findings, e.g. [2]. In addition, segmentation reduces the magnitude of the maximum tensile stress in the lining, although the effect is not major.

To quantify the likelihood for lining failure along the lining/jacket interface, the variation of the surface-flaw based (elemental) risk of rupture is computed [using Eqs. (1) and (5) at the centroids of membrane (ceramic) elements] and plotted as a function of the distance from the breech end. The results displayed in this figure show that, as anticipated, the risk of rupture takes on the largest values near the barrel ends and peaks at the muzzle end. Using Eq. (5) and the Weibull materials

statistical parameters for  $\alpha$ -SiC assessed in our previous work [5], the overall probability for failure of the lining during a single-shot ballistic event is computed as 0.0025 and 0.0023 for the single-piece and segmented linings, respectively. Thus, as suggested earlier, the probability for lining failure during a single-shot ballistic event is reduced by lining segmentation, but the effect is rather meager ( $\sim 8\%$ ).

### 3.2.2. Burst firing mode

In this section, the thermal and mechanical finite element analyses are used to study the effect of lining segmentation on the development of thermal stresses during a ten-round (burst) ballistic event. The firing rate is set to 10 rounds/min so that one round is fired every 6 s. Due to a relatively low firing rate and the fact that the film temperature (Fig. 4a) is very close to the room temperature at the time of 6 s following ignition, the film temperature and the forced-convection heat transfer coefficient for the burst ballistic event are assumed to be a periodic function of time with a period of 6 s. The values of these two quantities over one 6-s period are next assumed to be identical to the ones displayed in Fig. 4a,b, respectively, over the same time period.

The distribution of the temperature in the steel jacket along the lining/jacket interface at the times of 0.3 s, 1 s and 3 s after the firing of the tenth round are shown in Fig. 5b. A comparison of the results for a single-round ballistic event (Fig. 5a) and for a 10-round event (Fig. 5b) indicates that the temperatures in the later case can be higher by as much as 300 K and that the muzzle end is exposed to the highest temperature ( $\sim 1600$  K).

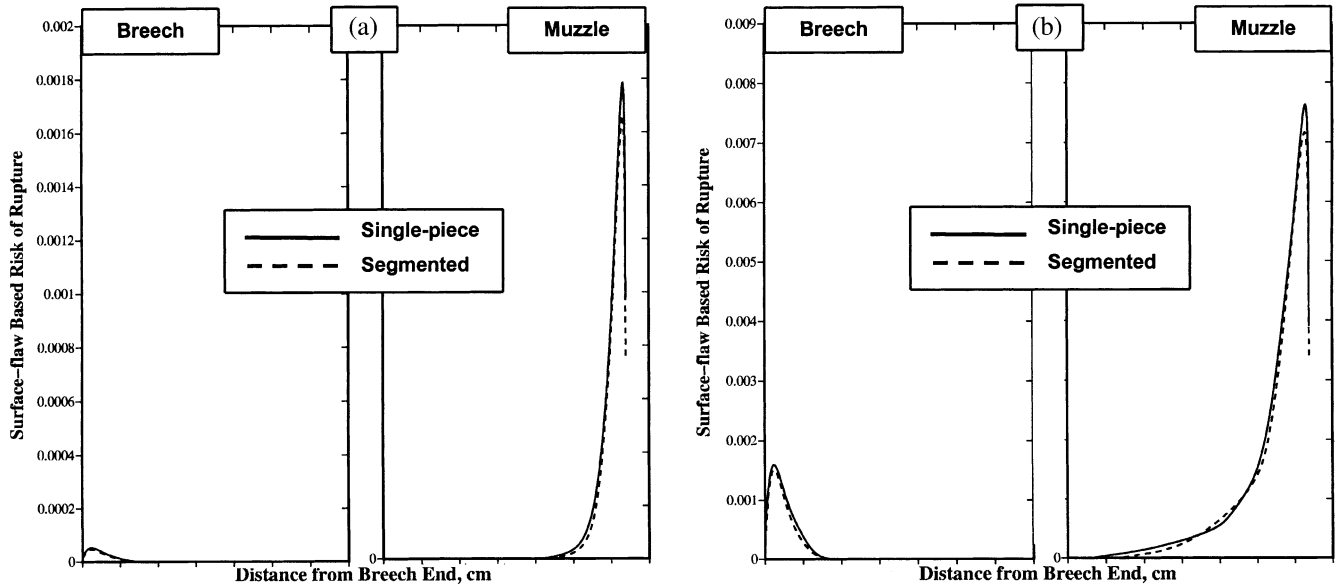


Fig. 7. Variation of the surface-flaw based risk of rupture in the ceramic lining at the lining/jacket interface with distance from the breach end of the barrel at a time of 1 s following the firing of the last round for: (a) single-shot and (b) burst firing modes.

The results displayed in Fig. 7b show the variation of surface-flaw based risks along the barrel length in both single-piece and segmented ceramic linings for the ten-round ballistic event, are compared with their single-shot counterparts displayed in Fig. 7a. The distributions of the axial  $\sigma_{zz}$  stress throughout the barrel wall near the muzzle and breach ends of the barrel at a time of 1 s after the last shot has been fired for the single-piece and segmented linings are displayed in Fig. 8a–d. It is seen that the ceramic lining near the muzzle and breach ends is still subjected to an axial tensile stress and that this stress is again the highest at

the lining jacket interface. In addition, the tensile stress regions extend substantially further from the barrel ends and magnitudes of the tensile stress are higher on average by 50–70 MPa than their single-shot counterparts (Fig. 6a–d). These findings suggest that the likelihood for failure of the ceramic lining, as experimentally observed e.g. [2], is expected to be higher for a burst than a single-shot firing mode. Moreover, the overall probability for lining failure is increased in the 10-round case from 0.0025 and 0.0023 to 0.0121 and 0.0099 for the single-piece and segmented linings, respectively. Again, lining segmentation is found to be

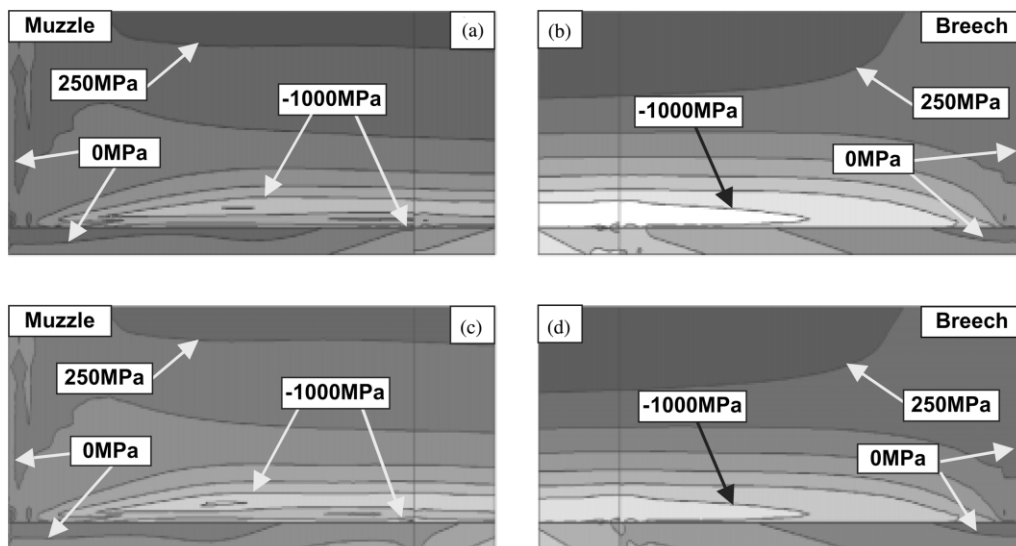


Fig. 8. Distributions of the axial stress near the muzzle and breach ends in barrels with a single-piece (a,b) and a segmented (c,d) lining at a time of 1 s after the tenth round has been fired.

beneficial in reducing the lining failure probability and this effect can be as high as 18% in the case of a 10-round firing event. These observations suggest that perhaps lining segmentation can be even more effective in longer, high firing-rate burst modes.

#### 4. Conclusions

Based on the results obtained in the present study the following main conclusions can be drawn:

- Thermal expansion of the steel jacket taking place during single-shot and burst ballistic events and the resulting development of tensile axial stresses in the ceramic lining appear to be the main cause for failure of the lining by formation of circumferential cracks near the barrel ends.
- Since the thermal expansion effects are more pronounced during burst firing events, the likelihood for ceramic failure is higher in this case relative to the single-shot ballistic event case. Specifically, the failure probability for ceramic failure is increased by a factor of  $\sim 5$  in a 10-round case with a 10 rounds/min firing rate relative to that in a single shot case.
- Lining segmentation has a beneficial effect in reducing the lining failure probability, particularly in the burst-firing mode. Specifically, the use of five identical segments in place of a single-piece lining can reduce the lining failure probability by as much as 18% in the ten-round firing mode.

#### 5. Nomenclature

$A$ :	surface area
$B_S$ :	surface-flaw risk of rupture
$m_S$ :	Weibull modulus for surface flaws
$N_S$ :	surface crack density function
$P_{fS}$ :	failure probability by surface flaws
$S$ :	component surface area
$\sigma$ :	stress
$\sigma_1, \sigma_2, \sigma_3$ :	principal stresses
$\sigma_n$ :	normal stress
$\bar{\sigma}_n$ :	average normal stress
$\sigma_{opS}$ :	multi-axial scale parameter
$\sigma_{oS}$ :	scale parameter for surface flaws
$\sigma_{zz}$ :	axial stress

#### Acknowledgments

The material presented here is based on work supported by the US Army Grant Number DAAH04-96-1-

0197. The authors are indebted to Drs Walter Roy, Fred Stenton and Bonnie Gersten of ARL for the continuing interest in the present work. The authors also acknowledge the support of the Office of High Performance Computing Facilities at Clemson University.

#### References

- [1] Application of Nonconventional Materials to Guns and Gun Tubes, National Materials Advisory Board, National Research Council, NMAB-423. National Academy Press, 1986.
- [2] Bunning EJ, Claxton DR, Giles RA. Liners for gun tubes—a feasibility study. *Ceramic Eng Sci Proc* 1981;2:509–519.
- [3] Stiglich JJ, Katz RN. A selected history of gun barrel liner materials development. US Army Research Laboratory, Sagamore Workshop on Gun Tube Wear and Erosion, Dupont Country Club, Wilmington, DE. 1996. p. 29–31.
- [4] Katz RN. *Ceram Eng Sci Proc* 1983;4:475–484.
- [5] Gruzicic M, DeLong JR, DeRosset W. Reliability analysis of hybrid ceramic/steel gun barrels, *J Mater Design Appl*; submitted
- [6] Katz RN. Ceramic gun barrel liners: retrospect and prospect. US Army Research Laboratory Sagamore Workshop on Gun Tube Wear and Erosion, Dupont Country Club, Wilmington, DE. 1996. p. 29–31.
- [7] Gough PS. Interior ballistics modeling: extensions to the one-dimensional XKTC code and analytical studies of pressure gradient for lumped parameter codes, Aberdeen Proving Ground, MD: US Army Research Laboratory, ARL-CR-460, 1988.
- [8] Chandra S. Reference manual for stand-alone version of NBHX's barrel radial heat conduction routines with burst fire and restart options XBR-3.0-001. East Amherst: Veritay Corp, 1990.
- [9] Corner J. Theory of the interior ballistics of guns. New York: Wiley, 1950.
- [10] Chandra S, Fisher EB. Simulation of barrel heat transfer. Final report, Contract No. DAAA15-88-D-0014. Delivery Order 0002. Aberdeen Proving Ground, MD: US Army Laboratory Command, US Army Ballistic Research Laboratory, 1989.
- [11] Conroy PJ. Gun tube heating. BRL-TR-3300. Aberdeen Proving Ground, MD: US Army Ballistic Research Laboratory, 1991.
- [12] Weibull W. A Statistical Theory of the Strength of Materials. Ingeniors Vetenskaps Akademien Hanglanger, 1939. (p. 154).
- [13] Batdorf SB, Crose JG. A statistical theory for the fracture of brittle structures subjected to nonuniform polyaxial stresses. *J Appl Mech* 1974;41(2):459–464.
- [14] Barnett RL. Fracture of Brittle Materials Under Transient Mechanical and Thermal Loading. US Air Force Flight Dynamics Laboratory, AFFDL-TR-66-220, 1967.
- [15] Freudenthal AM. Statistical approach to brittle fracture. Fracture and advanced treatise. In: Liebowitz H, editor. *Mathematical Fundamentals*. Academic Press, 1968. p. 591–619.
- [16] Batdorf SB, Heinisch HL Jr. Weakest link theory reformulated for arbitrary fracture criterion. *J Am Ceram Soc* 1978;61(7/8):355–358.
- [17] Author A. ABAQUS/Standard User's Manual Version 5.8. Providence, RI: Hibbitt, Karlsson, and Sorensen, Inc, 1998.